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PROBABILITY OF DETECTION (POD) ANALYSIS
FOR THE ADVANCED RETIREMENT FOR
CAUSE (RFC)/ENGINE STRUCTURAL
INTEGRITY PROGRAM (ENSIP)
NONDESTRUCTIVE EVALUATION (NDE)
SYSTEM DEVELOPMENT
VOLUME 3 – MATERIAL CORRELATION STUDY

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In the current environment of restricted budgets, aircraft components are often used beyond their design life. In order to avoid the large cost of replacing critical rotating parts as they reach their “safe-life” limits, a Retirement For Cause (RCF) program was implemented. The RFC program involves periodic nondestructive evaluation (NDE) inspections to assess the damage-state of components. Components with no detectable cracks are returned to service and those with detected cracks are discarded before they can cause an incident. This process allows parts with high life to be used to their full potential. The Air Force has embraced RFC and currently uses it to successfully manage component life for several of their gas turbine engines.

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Foreword

This is the third volume of a technical report prepared by the University of Dayton Research Institute for the Materials and Manufacturing Directorate (ML) of the Air Force Research Laboratory (AFRL), Wright-Patterson Air Force Base, Ohio. The work was performed under Contract Number F33615-95-C-5242 with Mr. Charles F. Buynak (AFRL/MLLP) as the Air Force project engineer. The technical effort was performed between 29 September 1995 and 31 December 1999, with Dr. Alan P. Berens of the University of Dayton Research Institute as the principal investigator.

The final report of this work comprises three volumes. Volume 1 presents a description of changes made to the probability of detection (POD) analysis program of Mil-STD-1823 and the statistical evaluation of modifications that were made to version 3 of the Eddy Current Inspection System (ECIS v3). Volume 2 contains the Users Manual for the version 3 update of the POD program. The results of a separate study for predicting POD from specimens of like geometry and materials are presented in Volume 3.

Section 1
Introduction

In the current environment of restricted budgets, aircraft component parts are often used beyond their design life. In order to avoid the large cost of replacing critical rotating parts as they reach their “safe-life” limits, a Retirement For Cause (RFC) program was implemented. The RFC program involves periodic nondestructive evaluation (NDE) inspections to assess the damage-state of components. Components with no detectable cracks are returned to service and those with detected cracks are discarded before they can cause an incident. This process allows parts with high life to be used to their full potential. The Air Force has embraced RFC and currently uses it successfully to manage component life for several of their gas turbine engines.

Managing the structural integrity of engine parts through the RFC program requires quantifying the capability of the NDE system used in the inspections. The RFC uses the highly automated Eddy Current Inspection System (ECIS) developed by Veridian. The capability of the RFC/ECIS has been quantitatively evaluated by inspecting specimen sets of representative material by geometry combinations. The ECIS response ($\hat{a}$) at cracks of known size (a) are then analyzed to estimate the probability of detection (POD) as a function of crack size, or POD(a). The reliably detected crack size, a_{90}, defined as the crack size for which POD(a_{90}) = 0.90, is used as the one number characterization of the ability of ECIS to detect cracks in the material by geometry combination.

The concept of obtaining POD(a) from $\hat{a}$ versus a data is shown in Figure 1. The probability of detection of a random crack of some fixed size is determined from the scatter in the NDE system response about the mean response for cracks of that given size [1]. Experience has shown that a linear fit of log $\hat{a}$ versus log a is often a reasonable model for the mean response over some range of crack sizes. In a range of crack sizes for which the linear fit is reasonable and the scatter about the fit is normally distributed and does not depend on crack size, POD(a) will be a cumulative normal distribution function with μ and σ as given by the following equations:

$$\mu = (\log \hat{a}_{dec} - B_0)/B_1 \tag{1}$$

$$\sigma = s/B_1 \tag{2}$$

where

$$\log \hat{a}_i = B_0 + B_1 * \log a_i + e_i, \tag{3}$$

and e_i = the difference in response, $\hat{a}_i$, of crack i from the mean of all cracks of size a;
s = is the standard deviation of e_i;
$\hat{a}_{dec}$ = is the response decision threshold for a crack indication;
B_0,, B_1, and s are fit parameters that are estimated from the data.

The a_{90} value is then given by the equation:

$$a_{90} = \exp(\mu + 1.282*\sigma). \tag{4}$$

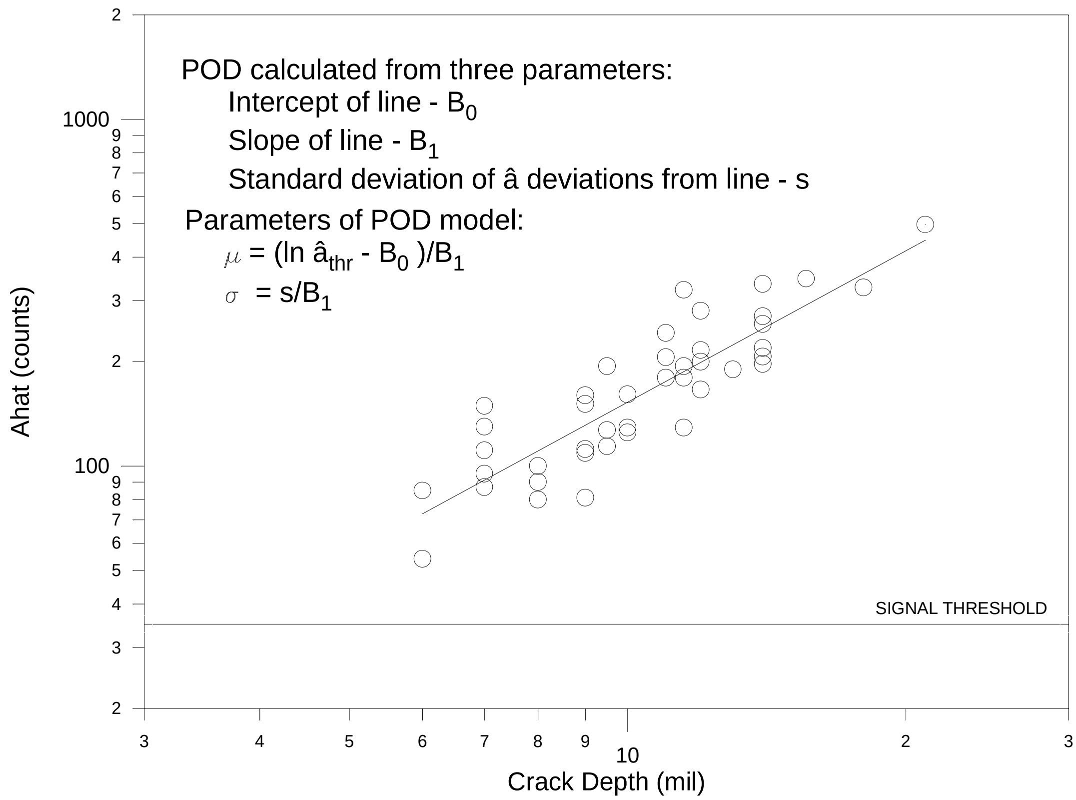

Figure 1. Schematic for Obtaining POD*(a)* from *â* versus *a* Data

To date, appropriate material/geometry combinations have been used to simulate real inspections for the POD(*a*) characterization of RFC/ECIS capability, and the three parameters of the *â* versus *a* analysis are estimated directly from the inspection results. To avoid the necessity of producing specimen sets for all materials by geometry combinations that will be inspected, a method for correlating POD results between specimen sets is being sought. Two characterization concepts to account for the differences in geometry by material combinations have been suggested. These concepts attempt to predict the unknown parameters of the log *â* versus log *a* fit for one geometry of one material, from inspections of three similar specimen sets, (1) the same geometry of a second material, (2) flat plate data of the same material, and (3) flat plate data on the second material. Each concept attempts to predict B_0, B_1, and *s*, the unknown parameters of the log *â* versus log *a* fit, from values obtained from inspections of the other three specimen sets. Because these methods involve material-based adjustments to the parameters obtained from the same geometry, these methods are also referred to as material correlation methods. The two material correlation methods are referred to as the “difference” and “ratio” methods, since the parameters of the missing combination are obtained either from differences or ratios of the parameters from the available sets.

To further demonstrate the concept of material correlation, Table 1 represents example components with five types of materials and five types of geometries. Parameters for material and geometry combinations in the first row and first column are assumed to be known.

Parameters for all other material and geometry combinations must be inferred from the material correlation method.

Table 1. Geometry – Material Combinations

	Geometry				
Material	1	2	3	4	5
1	☆	☆	☆	☆	☆
2	☆	?	?	?	?
3	☆	?	?	?	?
4	☆	?	?	?	?
5	☆	?	?	?	?

A material correlation study performed by Veridian in September 1999 [2] was motivated by the need to minimize the required number of specimen sets while providing the most accurate inspections possible. The primary proposal of the material correlation project was that the ratio of the eddy current responses from cracks of the same size in two different materials of the same geometry should equal the ratio of the eddy current responses from cracks in specimens made from the same two materials having a different geometry. Because the $\hat{a}$ versus a data is constructed in a log-log domain, the proposed materials correlation assumption equates to parameter differences.

The goal of the study was to show whether or not reliability analysis results obtained from the eddy current inspection of certain specimen sets could be used to predict the reliability analysis results for another specimen set of like material but with different geometries. For example, can the reliability analysis parameters be determined for Ti-6246 bolt hole specimens using bolt holes in IN 718 and flat plate specimens of IN 718 and Ti-6246? To test this, the predicted probability of detection was compared to the actual POD using combinations of materials and geometries that already exist, as shown in Table 2.

Table 2. Material Correlation Test Matrix

	Geometry	**Material**
1	0.342" Bolt Hole	IN 718
2	0.460" Bolt Hole	Ti-6246
3	Flat Plate	Ti-6246
4	Flat Plate	IN 718

Researchers at the University of Dayton Research Institute (UDRI) reviewed, analyzed, and evaluated the study to predict POD through the material correlation study performed by Veridian. This report will present a discussion of requirements for performing materials correlation in Section 2, examination of the data acquisition methods of the study in Section 3, and an evaluation of the POD inference methods using the data collected in the study in Section 4. Finally, general recommendations for optimizing the material correlation study will be provided in Section 5, and Section 6 summarizes the study and its results.

Section 2

Requirement for Performing Material Correlation Studies

Many variables must be controlled to acquire eddy current responses from different sets of test specimens if they are to be useful for material correlation studies. Some of the known variables that can affect the amplitude of the eddy current responses from a crack are listed in Table 3.

Table 3. Eddy Current Inspection Parameters

Category	Variable	Controllable
Probe	Inherent Coil Sensitivity	✓
	Relative/Differential Sensitivity	✓
	Coil size	✓
	Lift-off	✓
Instrument	Gain	✓
	Phase Angle	✓
	Frequency	✓
	Filters	✓
Specimen	Conductive	✓
	Crack Orientation	
	Crack Opening	
	Aspect Ratio Depth	
	Residual Stress	
	Grain Size	
Inspection	Step Size	✓
	Calibration Variation	
	Scan Speed	✓
	Material Noise	✓
	Random Noise	✓
Geometry	Lift-off	✓
	Geometric Variables	✓

An extensive amount of work is required to examine each variable and determine the extent of how and why it affects the eddy current response data acquired from cracks in reliability specimens. It would be difficult, if not impossible, to control all of the variables. If they are not controlled, the effect of not controlling them must be understood and predicted. This is the crux of the problem. Since many of these variables necessitate different material/geometry combinations, they

cannot be strictly controlled. Therefore, they must be understood and their behavior predicted. The question that remains unanswered is: How well can this be done?

Phase angle calibration is a good example of how difficult it is to manage a variable during eddy current inspection. Differential eddy current probes are commonly used for RFC-type inspections to achieve the signal-to-noise ratios needed to detect small cracks. The differential nature of the probes greatly affects the phase angle setting in the eddy current instrument. All responses from the probe result from the difference between the signals coming from the two coils. Thus, the phase angle setting is as much the result of the imbalance of the two coils as it is the interaction of the eddy currents with the electrical properties of the material. The responses from each coil are dependent on the material, the crack, and the relationship between each coil and the metal in its proximity. It is difficult to determine how each differential probe responds to the unique combination of its own imbalance, the specimen, geometry type, and the crack. Acquiring eddy current responses from differential probes from three specimen sets, and then using the data to predict the eddy current response for cracks in a fourth specimen set, requires a thorough understanding of the probe's interaction with the fourth specimen's material and geometry, as well as the cracks.

Essentially, the problem in this example is twofold:

1. Whether the unknown calibration phase angle could be predicted for a material/geometry combination based on the known phase angles of three other material/geometry combinations
2. Given that unknown calibration phase angles can be predicted and the phase angle can be set accordingly, whether the crack response (phase and amplitude) could be predicted for this material/geometry combination from the crack response on different cracks found in the other three material/geometry combinations.

These two problems must be resolved in light of the other variables, such as lift-off. The question deals with modeling the phase response and then the crack response behavior at that phase angle setting.

Another issue that complicates any effort to do materials correlation is the application of the materials correlation results to real engine part inspections. The conditions under which the materials correlation tests are conducted must be reproduced in the inspection of real engine parts. Such inspection conditions include coil type, inspection algorithm, calibration (phase and gain calibration), scan rates, filter settings, inspection parameter values, and others. Often, however, the particulars of a real engine part inspection will constrain these variables. This means that the materials correlation tests must be designed with the inspection in mind.

An example of this would be bolt hole inspection of a material for which there is no POD specimen set. These inspections are conducted with noncontact bolt hole probes scanning at a very high rate. Many bolt hole inspections are conducted at 1500 RPM. A bolt hole diameter of 0.5 inches gives a surface velocity of about 40 inches per second. Performing a materials correlation using flat plate and bolt hole specimens of the appropriate materials would require attempting to collect flat plate data using proper controls. However, it would be virtually impossible to match surface velocity on the flat plate specimens because the RFC linear axes have a maximum velocity of 300 inches per minute, or 5 inches per second. The flat plate

specimens could be mounted in a test fixture clamped to the turntable, which is routinely done, and the turntable rotated. The current flat plate fixture holds specimens at a radius of about 7 inches. At the maximum turntable speed of 18 revolutions per minute, the surface velocity would be only 14 inches per second. Since it is apparent that the surface velocity cannot be matched, the only alternative is to assume that the slower surface velocity can be accounted for by scaling all parameters that are scan-speed dependent, such as filter settings and inspection parameters.

Another variable that would need to be controlled in this example is lift-off. Since bolt hole probes are noncontact, the flat plate specimens would have to be scanned with the same lift-off, which poses implementation challenges for a surface probe. Another issue is the type of notch used to calibrate the probe. Bolt hole probes are calibrated using corner notches, and surface probes are calibrated using surface notches. The surface probes on the corner notches used for bolt hole calibration would have to be calibrated to remove this source of variation. Since this is impossible, an alternative would be to use the bolt hole probe to perform the flat plate specimen inspection. Obviously, this would be difficult if not impossible, especially in light of the need to keep lift-off uniform; however, it has the advantage of removing the coil as a variable.

Another complication in this example is the need to control the inspection routine. The bolt hole inspection routine, including inspection parameters, step sizes, and sampling rates, would have to be used on the flat plate inspection. If any of these steps cannot be controlled, then the results of the tests and models would depend upon the validity of the assumptions used to ignore the differences.

It may be impractical, if not impossible, to control the variables. In Veridian’s attempt to test a proposed model for material correlation, an application was selected that would allow many of the variables to be controlled. Their tests and controls will be discussed in more detail in the next section. While Veridian used flat plate and bolt hole specimens, they tested the materials correlation model using a scallop setup and inspection method. They had to design a special probe that could fit into a bolt hole and also ride on a surface specimen. They used a special phase and gain calibration routine. In effect, Veridian created a hybrid test condition to avoid the problems that would be encountered in an attempt to apply materials correlation to a real inspection. This is not a criticism of Veridian’s methods, but a concession to the difficulty of controlling the variables.

From this discussion, it is clear that each inspection application forces a unique set of testing conditions on the material correlation test setup. The uniqueness of the test conditions almost assures its inapplicability of results to other applications. This narrow applicability results in the requirement of three sets of data for each and every possible material/geometry combination for which there are no specimen sets. Materials correlation trades the cost of one set of new specimens for the cost of three POD runs of data on existing specimens, plus the engineering cost of designing and creating the scan plans and possibly other hardware (such as probes) to carry out these runs. This assumes that the required test conditions can be met.

One final complicating factor is that not all geometries have a corresponding POD specimen set in any material. This case indicates the existence of what might be called a geometry correlation; that is, POD is determined on an existing set of specimens of one geometry and it is assumed that these results apply to another geometry. For instance, a scallop set of specimens might be used to represent an anti-rotation tab fillet radius. Issues of probe, coil, lift-off, and curvature further complicate the assumptions made for materials correlation.

Section 3
Examination of Data Acquisition

As mentioned in the previous section, Veridian created a hybrid test condition, which was essential for testing materials correlation. Veridian understood this, as shown by the following quote from their report: “A primary concern in this project was to attempt to minimize any variation in the multitude of parameters in data collection, including, among others, gain, phase, lift-off, coil orientation, filtering, scan speed and signal processing”. As mentioned earlier, Veridian designed and built a special probe that would allow them to scan both the bolt hole and flat plate specimens. The probe could be configured in two different ways to further accommodate this constraint. Veridian also created special software to allow the routine to perform inspections on both specimen sets. Necessity dictates differences in setup for these different inspections, but as noted by Veridian, “Critical functions were performed by common subroutines.” Inspection setup was chosen to be consistent with the scallop inspection.

To perform gain calibration, Veridian used the master set of reference standards to avoid additional variation due to notch parameter uncertainties. They performed phase calibration on the IN 100 reference block across the long notches. The notch signal was then rotated into the vertical component of the impedance plane. For Ti-6246 materials, an additional phase calibration was performed. Gain calibration for both materials was performed on the IN 100 block after phase calibration on the IN 100 notch. For Ti-6246 specimens, the phase was rotated after gain calibration to be consistent with the phase determined on the Ti-6246 notch. This strategy was used to reduce variation caused by gain calibration – Veridian stated, “This method of calibration was to provide consistent gain setup across all data sets while compensating for phase rotation in dissimilar metals” [2]. The propriety of such a protocol is arguable, but their attempt further emphasizes the difficulty in performing a good material correlation.

Veridian describes their method of selecting which cracks to use on their test. The need for this selection process arose out of the design of the specimen set. Since the specimen set was designed to accommodate fluorescent penetrant inspections, there were multiple cracks on any given specimen, which could be in different orientations. Veridian eliminated those cracks that were inappropriate for this test.

Veridian used a D20 differential coil scanned at 60 inches per minute (1 inch per second), with a sampling rate of 1000 points per second. The high pass filter was set at 5 Hz, and the low pass filter at 100 Hz. For a D20 coil scanning at this rate, a typical flaw frequency would be in the range of 30 to 60 Hz. These filter settings appear acceptable for this configuration. Other parameters were not identified in their report, but there is reason to believe that the parameters are set correctly and properly controlled, especially in light of the care demonstrated in the rest of the setup to maintain strict control. Overall, Veridian took great care to control the conditions under which data is collected for this test. These ideal circumstances should be adequate to test the hypotheses inherent in material correlation.

Section 4
Evaluation of POD Inference Methods with Test Data

As stated earlier, two methods have been proposed for inferring the POD(a) function from $\hat{a}$ versus a data: the difference method and the ratio method. The methods are described and applied to the data collected on ECIS inspections of IN 718 and Ti-6246 bolt hole and flat plate specimen sets.

4.1 Proposed Correlation Methods for Inferring POD

Veridian designed and conducted a special experiment using bolt hole specimens to validate or refute the proposed material correlation methods. The ECIS system was used to inspect four specimen sets: IN 718 bolt holes and flat plates, and Ti-6246 bolt holes and flat plates. The inspections were conducted to provide data that would mimic the bolt hole inspections as closely as possible. The data analysis to evaluate the two methods assumed that the objective was to estimate the POD(a) capability for IN 718 bolt hole inspections under these test conditions from the known log $\hat{a}$ vs log a parameters of the other three combinations of geometry and material. Calculations of the POD parameters for the three known combinations are shown in the following equations, where *TiFP* = Titanium Flat Plate, *TiBH* = Titanium Bolt Hole, *InFP* = IN 100 Flat Plate, and *InBH* = IN 100 Bolt Hole.

For the Ti-6246 flat plates, let

$$\log \hat{a}(TiFP) = B_0(TiFP) + B_1(TiFP)*\log a + e(TiFP), \tag{5}$$

where $e\ (TiFP)$ is N(0,$s\ (TiFP)$). For the IN 718 flat plates, let

$$\log \hat{a}(INFP) = B_0(INFP) + B_1(INFP)*\log a + e(INFP), \tag{6}$$

where $e\ (INFP)$ is N(0,$s\ (INFP)$). For the Ti-6246 bolt holes, let

$$\log \hat{a}(TiBH) = B_0(TiBH) + B_1(TiBH)*\log \mathrm{a} + e(TiBH), \tag{7}$$

where $e\ (TiBH)$ is N(0,$s\ (TiBH)$). The objective is to estimate the parameters of the fit that would be obtained if the IN 718 bolt hole specimens were available for inspection. That is, the objective is to estimate *B0(INBH)*, *B1(INBH)*, and *s (TiBH)*.

4.1.1 Difference Method

The difference method for estimating the IN 718 bolt hole parameters is partially related to the assumption that the signal response ratio between the flat plate specimens of two different materials would be the same as the signal response ratio between bolt holes of the same two different materials. Under this assumption, the following equation applies:

$$\hat{a}(INBH)/\hat{a}(TiBH) = \hat{a}(INFP)/\hat{a}(TiFP). \tag{8}$$

Then,

$$\log \hat{a}(INBH) - \log \hat{a}(TiBH) = \log \hat{a}(INFP) - \log \hat{a}(TiFP). \tag{9}$$

Substituting equations (5) through (7), rearranging terms and equating coefficients yields the following equations:

$$B_0(INBH) = B_0(TiBH) + [B_0(INFP) - B_0(TiFP)], \tag{10}$$

$$B_1(INBH) = B_1(TiBH) + [B_1(INFP) - B_1(TiFP)], \tag{11}$$

and

$$e\ (INBH) = e\ (TiBH) + [e\ (INFP) - e\ (TiFP)]. \tag{12}$$

The calculations of the slope and intercept of the log $\hat{a}$ versus log a fit for the IN 718 bolt holes is straightforward from equation (8) and are given in equations (10) and (11). The assumed physical basis for assigning some validity to the difference method is that the slope and intercept of the fit are obtained from the slope and intercept of the bolt holes of the other material and then adjusted by a material factor that is calculated from the flat plates, i.e., a different geometry. However, the physical basis justifying the estimation of the parameter s (INBH) is not understood.

In the $\hat{a}$ analysis, *s (INBH)* is the standard deviation of the normal distribution of the residuals, *e (INBH)*, of the $\hat{a}$ values from the linear log-log fit implied by equation (3). Equation (12) cannot be used to calculate *s (INBH)* because the co-variances of the residuals from the fit of the other materials by geometry combinations are not known. In the proposed difference approach, the somewhat arbitrary assumption is made that the difference between the residual standard deviations of the IN 718 and Ti-6246 bolt holes would equal the difference between the residual standard deviations of the IN 718 and Ti-6246 flat plates. This assumption results in the formula shown in equation (13). Note that equation (13) is the result of an arbitrary assumption that would not be valid for all applications. Reasonable data could be postulated that would lead to the impossible situation of a negative standard deviation.

$$s\ (INBH) = s\ (TiBH) + [s(INFP) - s\ (TiFP)] \tag{13}$$

Equations (10), (11), and (13) summarize the difference method proposed for predicting the $\hat{a}$ versus a parameters for the missing specimen set. These parameters were proposed for use in equations (1), (2), and (4) to characterize the *POD(a)* function and the a_{90} value for selected $\hat{a}_{thr}$ values.

4.1.2 Ratio Method

The concept of the ratio method is somewhat similar to that of the difference method, with the exception that the adjustments for material differences are made in terms of the ratios of

parameters rather than the differences. No justification for these somewhat arbitrary assumptions, in terms of differences in signal responses, is made. In this method, it is simply assumed that:

$$B_0(INBH) = B_0(TiBH) * [B_0(INFP) / B_0(TiFP)], \tag{14}$$

$$B_1(INBH) = B_1(TiBH) *[B_1(INFP) / B_1(TiFP)], \tag{15}$$

and

$$s\,(INBH) = s\,(TiBH) *[s\,(INFP) / s\,(TiFP)]. \tag{16}$$

The ratio method will not result in impossible estimates for the missing parameters, but large biases can be introduced if there are significant differences in the slope or standard deviation estimates due to a specific specimen set.

4.2 Application of the Methods

Veridian collected four sets of data that can be used to evaluate any proposed method for inferring POD(*a)* for a missing specimen set. The objective for collecting these experimental data was to provide a database that would permit estimating the POD(*a*) parameters from the proposed methods while, at the same time, having a data set that represented a true set of $\hat{a}$ versus *a* data from the missing geometry-material specimens. The inspection data were from IN 718 and Ti-6246 bolt hole and flat plate specimen sets and were obtained under carefully controlled conditions that were similar to a standard bolt hole inspection. Plots of the four sets of $\hat{a}$ versus *a* data are presented as Figures 2 through 5. Parameters of the fit for each specimen set were obtained for the widest crack size range in which the required statistical assumptions were reasonably valid. The range of crack depth validity for these POD(*a)* analyses was approximately 8 to 22 mil. The estimates of the parameters of the fits to these data are presented in Table 4.

Table 4. Fits of log $\hat{a}$ versus log *a* from Inspection Data

	IN 718 BH	**Ti-6246 BH**	**IN 718 FP**	**Ti-6246 FP**
Flaw Depth Range:	8 – 21	8 – 25	8 – 24	7.8 – 19.7
Cracks Analyzed:	35	40	21	28
Signal Minimum:	500	500	200	200
Signal Maximum:	8192	8192	8192	8192
Parameter	**Parameter estimate from inspection data**			
Intercept (B0)	5.16	4.04	3.76	4.26
Slope (B1)	1.12	1.53	1.52	1.40
Residual Error	0.201	0.162	0.180	0.152
Repeatability Error	0.058	0.032	0.119	0.036
Sigma	0.183	0.107	0.131	0.110

The parameter estimates from the flat plate specimens and one of the bolt hole specimen sets were then used to estimate the parameters of the missing bolt hole inspection using both the difference and ratio inference methods.

4.3 Data Analysis

The comparison of the direct and inferred POD(a) results from the two methods are presented in the following subsections.

4.3.1 Difference Method

The difference method parameter estimates of the log $\hat{a}$ versus log a fit for the missing bolt hole specimens are presented in Table 5. Also repeated in Table 5 are the values obtained from analysis of the actual data. The difference method would underestimate the intercept and sigma and overestimate the slope when the IN 718 bolt holes were the unknown set. The reverse was true when the Ti-6246 bolt hole parameters were estimated. In this example, the difference correction for materials that is obtained from the flat plate specimens degrades the fit that would be obtained simply by ignoring material differences. The intercept and slope parameters from the other material are closer to the actual values than are those obtained by the additional “material” adjustment.

Table 5. Comparison of log $\hat{a}$ versus log a Parameter Estimates from the Difference Method

	IN 718 BH		Ti-6246	
Parameter	**Data**	**Inferred**	**Data**	**Inferred**
Intercept (B0)	5.16	3.54	4.04	5.66
Slope (B1)	1.12	1.66	1.53	1.00
Sigma	0.183	0.127	0.107	0.162

To see the effect of the differences in parameter estimates on the characterization of inspection capability in terms of a_{90} values, a plot of a_{90} versus a_{thr} was generated for the approximate range of validity of the fits. These comparisons are presented in Figures 6 and 7 for the IN 718 and Ti-6246 bolt hole specimens, respectively. While it is not unusual for a_{90} values to differ by about 0.001 inch (1 mil) due to changes in probes and recalibrations, the differences of 3 to 4 mil at the smaller crack sizes are unacceptable. This is particularly true for the inferred Ti-6246 thresholds, since the a_{90} values for an inferred threshold would not be conservative. In a blind application of the method, there would be no way of knowing whether or not the results were not conservative.

4.3.2 Ratio Method

The ratio estimates for the parameters of log $\hat{a}$ versus log a fit for the missing bolt hole specimens are presented in Table 6. Also repeated in Table 6 are the values obtained from the data. The results are analogous to those obtained from the difference method. Again, the ratio correction for material obtained from the flat plate specimens degrades the fit that would be obtained simply by ignoring the material difference adjustment from the flat plates.

The plots of a_{90} versus a_{thr} for characterizing the IN 718 and Ti-6246 capability as a function of decision threshold using the ratio method are presented in Figures 8 and 9. Again the differences that would result from the inferred a_{90} are judged to be too large. As with the difference method, the inferred a_{90} value for the Ti-6246 bolt holes are not conservative.

Table 6. Comparison of log $\hat{a}$ versus log a Parameter Estimates from the Ratio Method

	IN 718 BH		Ti-6246	
Parameter	**Data**	**Inferred**	**Data**	**Inferred**
Intercept (B0)	5.16	3.57	4.04	5.85
Slope (B1)	1.12	1.67	1.53	1.03
Sigma	0.183	0.127	0.107	0.154

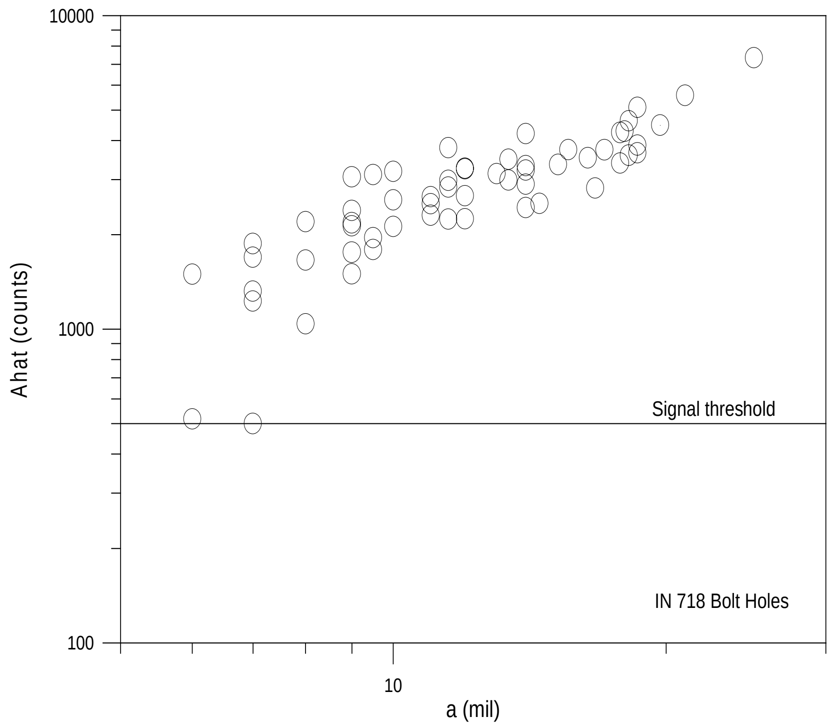

Figure 2. *â* versus *a* for IN 718 Bolt Hole Specimens

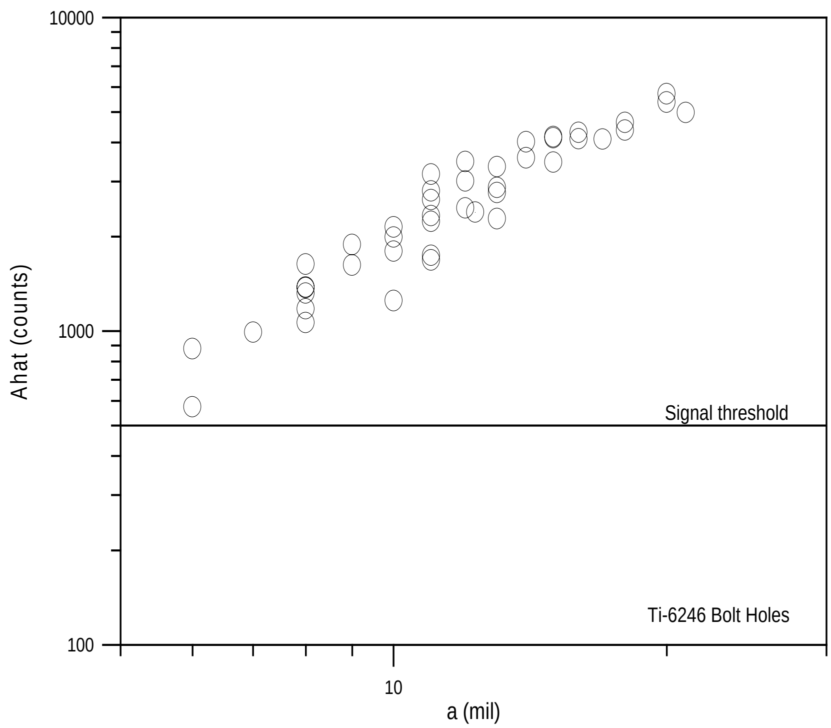

Figure 3. *â* versus *a* for Ti-6246 Bolt Hole Specimens

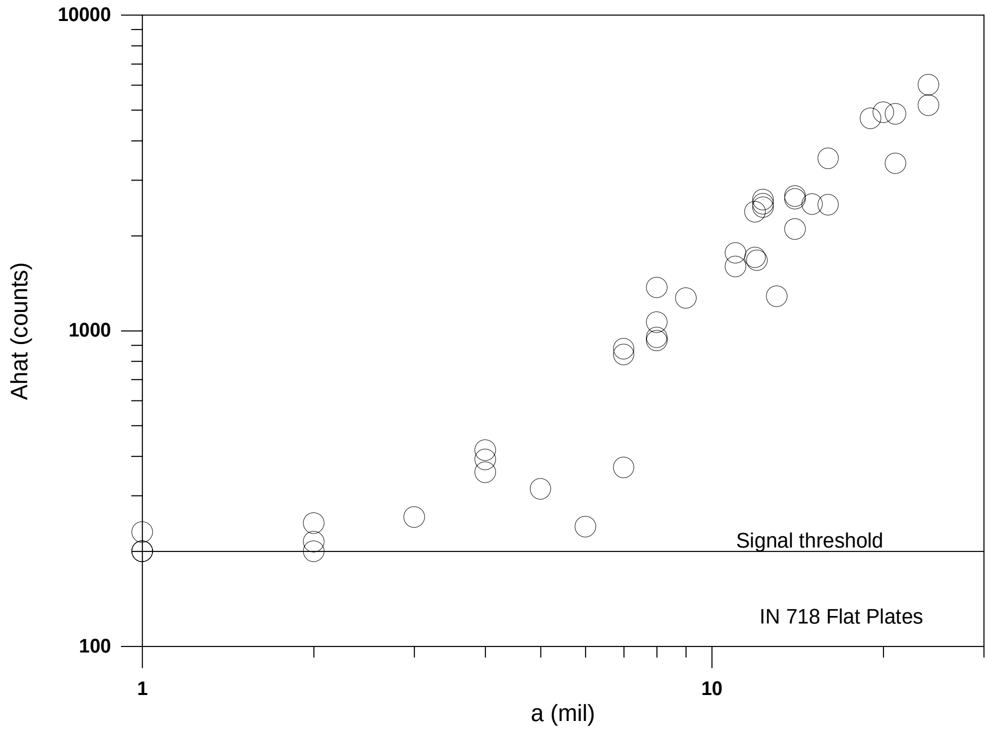

Figure 4. $\hat{a}$ versus a for IN 718 Flat Plate Specimens

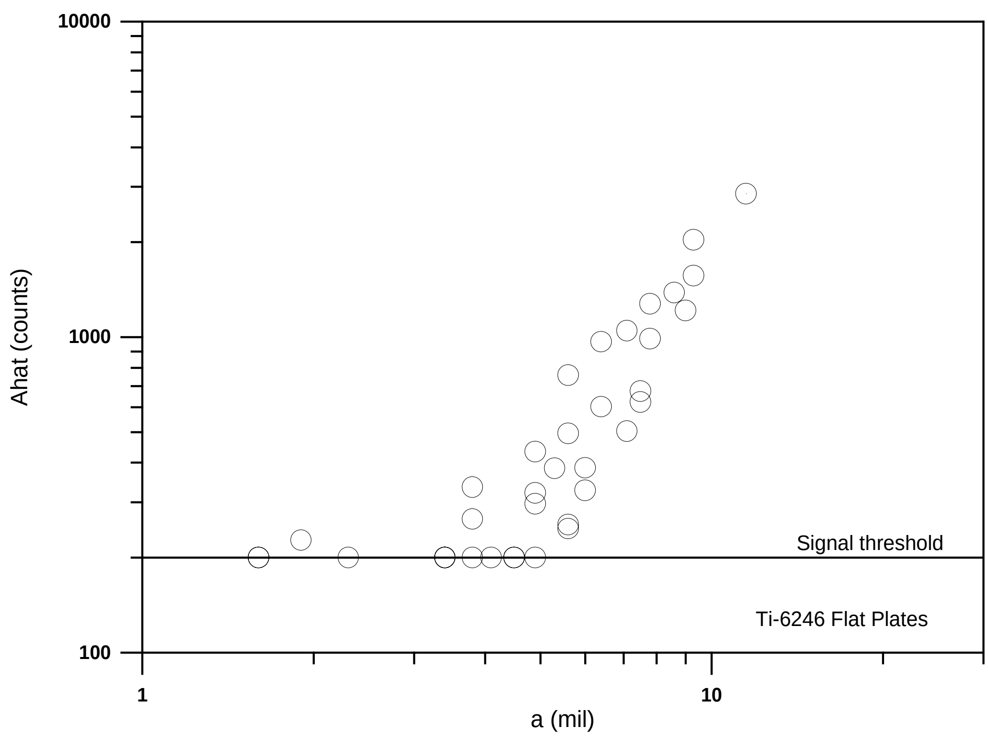

Figure 5. $\hat{a}$ versus a for Ti-6246 Flat Plate Specimens

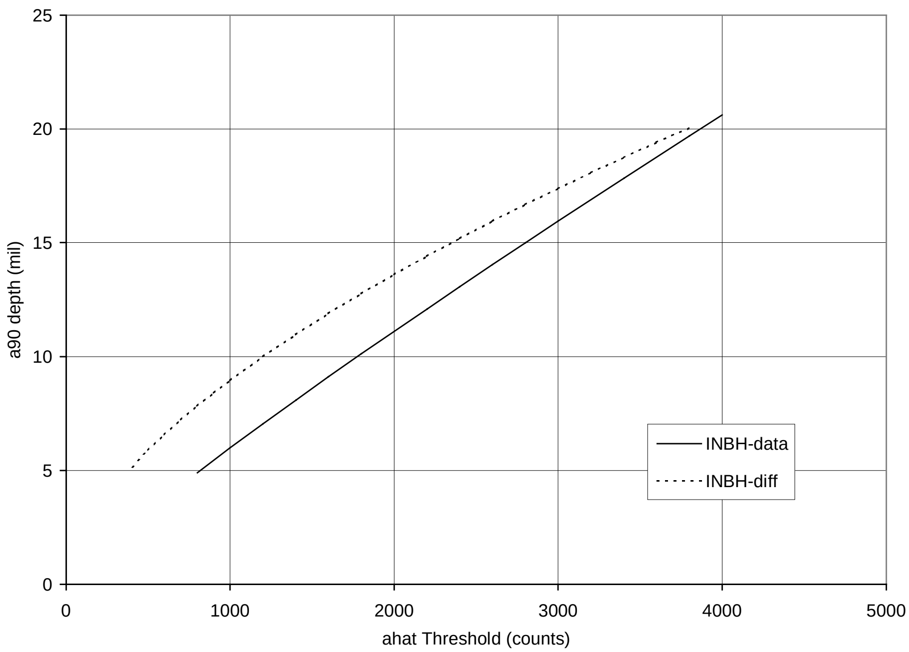

Figure 6. Threshold Plot Comparing Results from Data and Use of the Difference Methods for IN 718 Bolt Hole Specimens

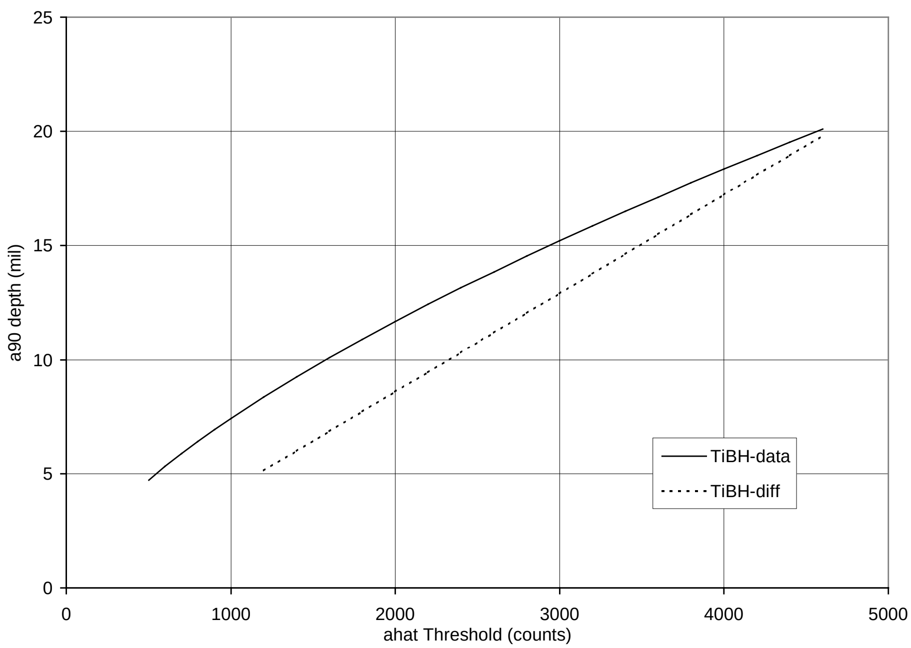

Figure 7. Threshold Plot Comparing Results from Data and Use of the Difference Methods for Ti-6246 Bolt Hole Specimens

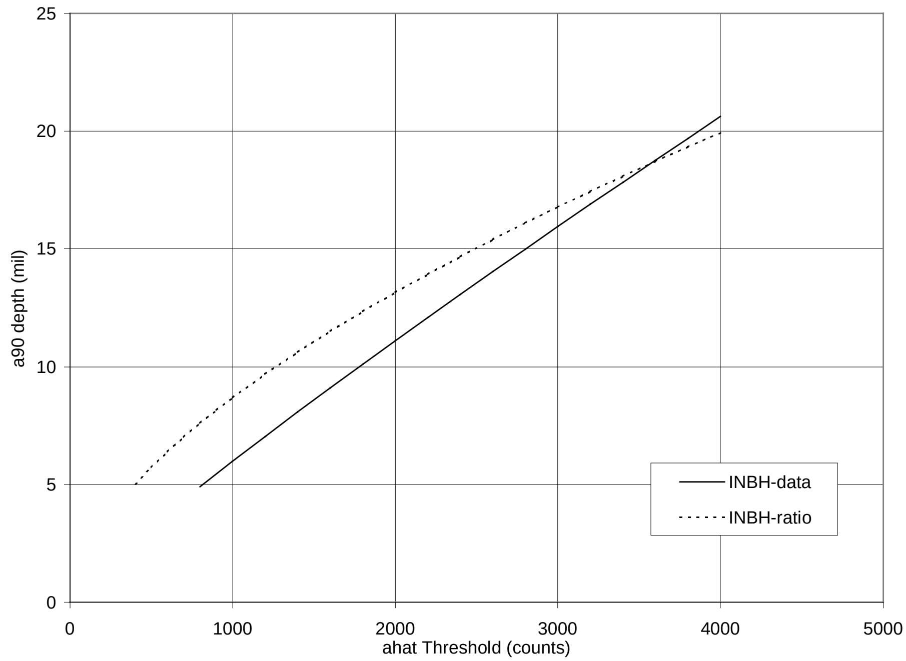

Figure 8. Threshold Plot Comparing Results from Data and Use of the Ratio Methods for IN 718 Bolt Hole Specimens

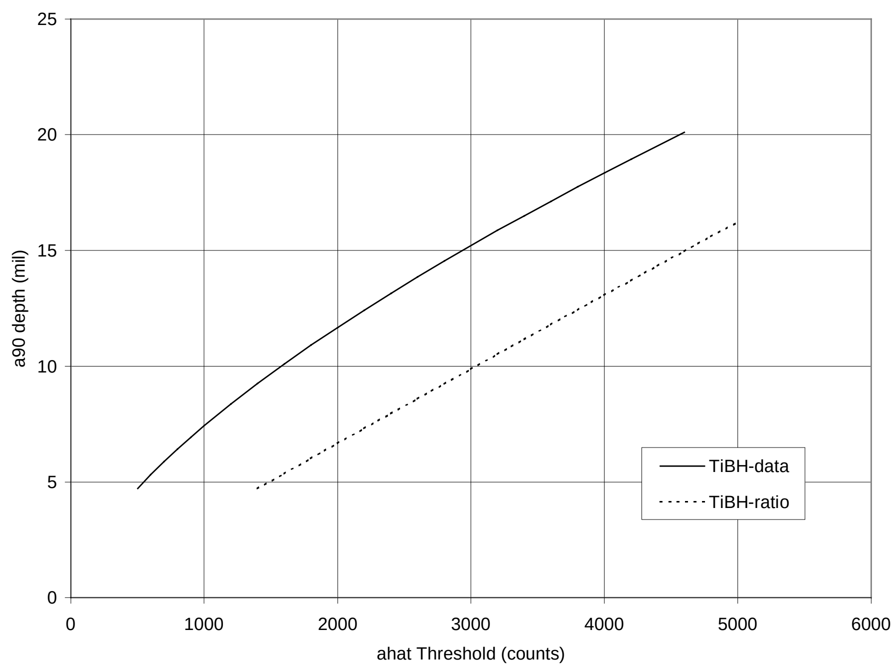

Figure 9. Threshold Plot Comparing Results from Data and Ratio Methods for Ti-6246 Bolt Hole Specimens

Section 5
Recommendations

As can be seen in the preceding analysis, the material evaluated in this report will not provide an adequate measure of POD capability. The alternatives from which the government must choose are therefore limited. The current approach to this problem, in effect, is to ignore material differences. When establishing the POD for a material/geometry combination that has no associated specimen set, the procedure is to use the specimen set of the same geometry of a different material. The POD is then assumed to be equal to that found from this specimen set, ignoring the difference in material. Veridian's report concludes by this quote: "In conclusion, the best possible prediction of POD is simply to match a similar geometry and use that data" [2].

The only other option for the Air Force is to conduct a study that will seek to establish a physical or empirical model of the eddy current response. The goal would be to account for the myriad variables, or show that any given variable does not appreciably affect the eddy current response. This approach would predict the POD from known responses on other material/ geometry combinations. The models evaluated in this report are effectively models without any physical or empirical bases. They are completely arbitrary and, in some ways, do not make sense physically. Unless and until a physical or empirical model is established for the eddy current response for these material/geometry combinations, the best approach seems to be to ignore material differences.

Section 6
Summary

The analysis of the data from the four specimen sets showed that the two proposed material correlation methods, the difference method and the ratio method, did not predict the $\hat{a}$ versus a parameters for the unknown specimen set with sufficient accuracy to justify their use. The correlation models were not based on physical considerations of the eddy current interactions with the material or geometry. Further complicating successful material correlation attempts is the difficulty in controlling all of the necessary eddy current inspection parameters. Many complicated material correlation reliability tests would have to be conducted using hybrid scan plans and probes, and an assortment of untested assumptions would have to be made. Even so, the results of such tests have been shown to be inadequate. The data strongly suggest that it is better to ignore material differences. The other option is to conduct a study establishing a physical or empirical model of the eddy current response. The goal would be to account for the myriad variables, or show that any given variable does not appreciably affect the eddy current response. This approach would predict the POD from known responses on other material/geometry combinations.

Section 7
References

1. Berens, A.P., “NDE Reliability Data Analysis,” ASM Metals Handbook, Volume 17, Nondestructive Evaluation and Quality Control, 9th Ed., American Society of Metals International, Materials Park, OH (1989).

2. “Material Correlation,” Communication by Veridian Engineering, September 1999.